Available online at www.sciencedirect.com

SciVerse ScienceDirect

Energy Procedia 37 (2013) 3911 – 3918

Energy Procedia

GHGT-11

Characterizations of the CCUS attributes of a high-priority CO_2 storage site in Wyoming, USA

R.C. Surdam[1], Z. Jiao[1], Y. Ganshin[1], R. Bentley[1], M. Garcia-Gonzalez[1], S.A. Quillinan[1], J.F. McLaughlin[1], P. Stauffer[2], H. Deng[2]

[1]*University of Wyoming Carbon Management Institute, 2020 Grand Ave. Suite 500, Laramie, WY 82070, USA*
[2]*Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87545, USA*

Abstract

Optimizing uncertainty reduction in evaluations of geological CO_2 storage site scenarios requires a robust database that allows an accurate reconstruction of the targeted storage rock/fluid volume, especially with respect to spatial heterogeneity. Previous numerical simulations of the Rock Springs Uplift site (southwest Wyoming, USA) relied on a generalized regional database to populate a homogenous rock/fluid volume based on average reservoir properties. The results from this approach yielded general insights into injection/storage characteristics but lacked specificity, resulting in performance assessments plagued by substantial uncertainty. To move from idealistic, highly generalized assessments to realistic, low-risk assessments of the Rock Springs Uplift, it was necessary to acquire high-resolution data specific to the storage site of interest (carbonate and sandstone reservoirs, and confining layers in an 8 km × 8 km area). The foundation of the new database is a 4,000-meter-deep stratigraphic test well, an 8 km × 8 km 3-D seismic survey, 290 meters of high-quality core, a specialized log suite, fluid samples, and a diverse set of analytical laboratory measurements. These data made it possible to correlate seismic attributes with observations from log suites, a VSP survey, core, fluid samples, and laboratory analyses, including continuous permeability scans. From seismic data, 3-D spatial distribution volumes of reservoir and confining layer properties were constructed that represent geological heterogeneity at the targeted CO_2 storage site. Consequently, the latest numerical simulations and performance assessments are characterized by substantially lower geological uncertainties.

The new CO_2 plume migration simulations – for a set of defined CO_2 injection rates and volumes – occupy larger rock/fluid volumes and display pronounced marginal irregularities when compared to early simulations derived from homogenous reservoir parameter volumes. The spatial distributions of the injected CO_2 plumes in previous simulations are conical with few marginal irregularities, whereas in the new simulations, the CO_2 plumes occupy a larger up-dip volume and display pronounced marginal irregularities. These irregularities denote zones of higher porosity and permeability, such as collapsed breccias associated with karst zones and/or dolomitized grainstone zones in the Madison Limestone.

Using the new numerical simulations which include heterogeneous rock/fluid parameter distributions, it is apparent that in all injection/storage scenarios of > 1 Mt/year CO_2, substantial displaced fluid production/treatment is essential to manage pressure and maintain the integrity of confining layers. The total dissolved solids concentrations of the formation fluids retrieved from the Madison Limestone range from 80,000 to 90,000 ppm, and will necessitate customized water treatment strategies and facilities at the surface. The new data and upgraded evaluations demonstrate that the Rock Springs Uplift in southwestern Wyoming remains an outstanding large-scale geological

Selection and/or peer-review under responsibility of GHGT
doi:10.1016/j.egypro.2013.06.289

CO_2 storage site, and provides a realistic basis for designing commercial CO_2 injection/storage operations on the Uplift.

The 2010 U.S. Environmental Protection Agency Greenhouse Gas Reporting Program reports that in the Greater Green River Basin of southwest Wyoming, the CO_2 emissions from stationary sources (sources that emit more than 25,000 tons of CO_2 per year) total 29+ million tons annually, or approximately 50 percent of Wyoming's annual CO_2 emissions. These CO_2 sources include coal-fired power plants, gas and trona processing plants, pipeline compression stations, chemical production facilities, and gas-field complexes, among others. The Rock Springs Uplift in the center of the Greater Green River Basin is ideally located to serve as a large-scale commercial geological CO_2 storage facility for half of all of Wyoming's industrial CO_2 emissions. The new numerical simulations suggest that the Madison Limestone has the ability to permanently store the annual CO_2 emissions from stationary sources in the Greater Green River Basin for 130 years (i.e., a total of 3.8 billion tons). The overlying Paleozoic Weber Sandstone on the Rock Springs Uplift has additional commercial-scale CO_2 storage capacity.

The Rock Springs Uplift has the attributes to serve as a regional CO_2 storage site, and importantly, this site could be used as a storage/surge tank to supply CO_2 to EOR projects throughout Wyoming.

Keywords: Type your keywords here, separated by semicolons ;

Introduction

The rationale for the WY-CUSP program (the flagship research effort at the University of Wyoming Carbon Management Institute) is four-fold:

1. Protect Wyoming's coal extraction and future coal conversion industries (provide commercial storage capacity for anthropogenic CO_2);
2. Provide a source of anthropogenic CO_2 for enhanced oil recovery projects (at current rates of CO_2 production from gas processing plants, it will take 150 to 200 years to recover Wyoming's stranded oil);
3. Retrieve reservoir information essential for expansion of natural gas storage in Wyoming (the state accounts for 11 percent of domestic natural gas production, but currently provides only 1 percent of the nation's natural gas storage capacity); and
4. Establish a more robust database for two important hydrocarbon reservoirs in Wyoming (substantially reduce uncertainty for all dynamic models of Tensleep-Weber Sandstone/Madison Limestone fluid-flow and rock/fluid systems).

At the request of Governor Dave Freudenthal, the Wyoming State Geological Survey inventoried and prioritized the potential geological CO_2 storage sites and reservoir intervals with the greatest storage capacity ([1] Surdam and Jiao, 2007). This study suggested that the Paleozoic Madison Limestone and Tensleep/Weber Sandstone have the greatest gas storage capacity (**Figure 1**), and that the Rock Springs Uplift and Moxa Arch are the two most promising CO_2 storage sites in Wyoming. The Rock Springs Uplift was ranked higher than the Moxa Arch simply because the Paleozoic storage reservoirs are closer to the surface.

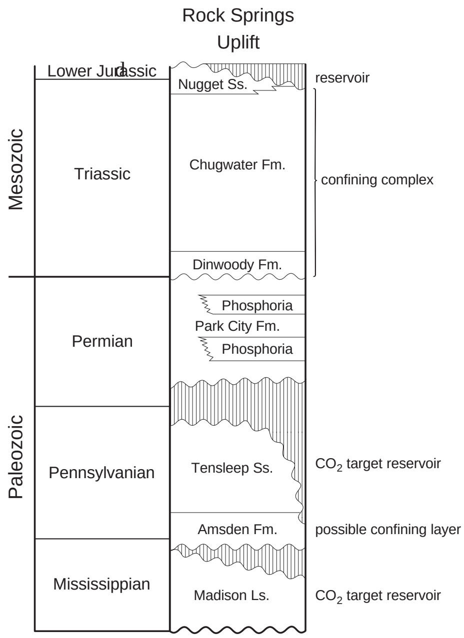

Figure 1. Modifie stratigraphic column of the Rock Springs Uplift identifying possible confining layers and CO_2 target reservoirs. Modifie from Love, Christiansen, and VerPloeg, 1993.

Rock Springs Uplift

The stratigraphic section in the vicinity of the Rock Springs Uplift (RSU) is characterized by a thick Paleozoic saline aquifer sequence. This reservoir sequence is overlain by a thick sealing complex consisting of confining layers in the Triassic Chugwater Formation capable of trapping helium, and multiple seals in the thick Cretaceous shale-rich stratigraphic section. Importantly, the CO_2 storage reservoirs on the RSU are separated from fresh water aquifers (USDW) by 8,000 vertical feet. The Paleozoic reservoir interval (approximately 1,000 feet thick) possesses the attributes required for successful gas storage, including fluid chemistry, porosity, fluid-flow characteristics, temperature, and pressure (i.e., regional burial history). The RSU is a doubly-plunging anticline characterized by more than 10,000 feet of closed structural relief. The Uplift covers an area of 50 miles by 35 miles, and in this huge area, only 19 wells penetrate the potential storage reservoir interval. For a summary of the geology of the Rock Springs Uplift, see [1] Surdam and Jiao (2007).

Initial storage capacity estimates for the Rock Springs Uplift

Estimates of CO_2 storage capacity for both the Madison Limestone and Weber/Tensleep Sandstone on the RSU were first published in 2007 ([1] Surdam and Jiao, 2007). The DOE FutureGen and USGS diagnostic protocols were used to make these initial storage estimates. Input data came from regional studies of the storage reservoir units and from 19 wells that penetrate the Paleozoic stratigraphic section on the RSU (approximately 2,000 square miles). Results indicated that on the RSU, the Weber Sandstone could accept 18 billion tons of CO_2 and the Madison Limestone could accept 8 billion tons of CO_2, for an estimated combined storage capacity of 26 billion tons. In summary, the Weber Sandstone and Madison Limestone within the RSU have huge CO_2 storage potential. The RSU satisfies geological CO_2 storage requirements well, displaying the following attributes: 1) thick saline aquifer sequence overlain by thick multiple sealing lithologies; 2) structural closure; 3) huge area; and 4) apparently suitable storage reservoir characteristics.

The next step in our investigation, in collaboration with Los Alamos National Laboratory (LANL), was to refine these initial CO_2 storage capacity estimates through the use of more dynamic high-resolution multiphase numerical models. Basically, the thrust of this step of the investigation was to combine the regional database with numerical models to evaluate a series of geological CO_2 storage scenarios for the RSU ([2] Surdam et al., 2009; [2] Stauffer et al., 2009). First, a 3-D geological model was constructed with EarthVision software. This model was then gridded using LaGrit software. Shallow and deep storage sites on the RSU were evaluated using the LANL CO_2-PENS software ([3] Stauffer et al., 2009). Next, a variety of CO2 injection and storage performance scenarios for the RSU were evaluated using the LANL numerical simulator (FEHM). The results of these evaluations are described in [2] Surdam et al., 2009; [3] Stauffer et al., 2009, and [4] Surdam et al., 2011).

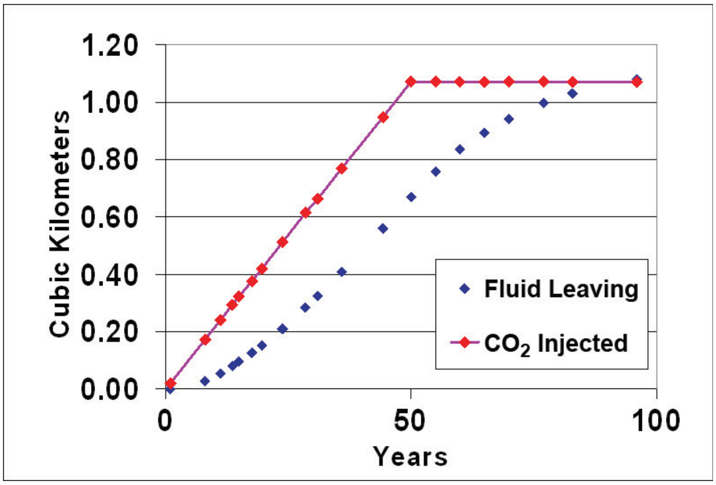

Figure 2. Relationship between total CO_2 injected in a 9-point injection simulation (750 Mt CO_2 over 50 years) and the amount of flud that must leave the storage domain to maintain boundary conditions in the numerical simulation (remain below frac pressures).

The following research-directing conclusions resulted from these performance assessments:

1. A critical problem in every geological CO_2 storage simulation completed for the RSU was the relationship between the volume of injected CO_2 and the displaced fluid that must leave the storage area to accommodate the injected fluid (**Figure 2**). The key questions are as follows: a) Can the accommodation space be found within the geological site to accept the huge volumes of fluid that must leave the storage domain?; and b) Given the heterogeneity of most geological settings (fluid-flow compartmentalization), can fluid migration pathways be maintained so that the displaced fluid can migrate from the storage domain to some external accommodation space without disrupting the confining units and destroying the integrity of the rock-fluid system, or must the displaced fluids be managed at the surface?

2. The greatest uncertainty in simulating CO_2 storage processes on the RSU is characterizing geological heterogeneity in three dimensions. The initial performance assessments of the RSU clearly demonstrate that the numerical simulations generally yield useful information relative to CO_2 injection and storage, but are inadequate in site-specific evaluations. Extrapolating only externally-derived data into performance assessments of specific targeted geological carbon storage sites is fraught with risks. For example, on the RSU, the nearest well penetrating the

storage reservoir interval lies 19 miles away from the selected storage site (< 2 miles south of Wyoming's largest stationary source of CO_2 emissions).

3. Also, the introduction of fluid-flow dynamics into the performance assessments resulted in reduction of the storage capacity estimates for both of the storage reservoir intervals.

Geological uncertainty reduction via a more robust database

The geological uncertainty described above that relates to the RSU site has been significantly reduced by the acquisition of an 8 km by 8 km (5 mile by 5 mile) seismic survey surrounding the targeted RSU storage site. In addition, an approximately 4,000-meter-deep (12,810 feet) stratigraphic test well was drilled in order to acquire a more robust database for the area covered by the 3-D seismic survey described above. The seismic survey was conventionally processed and later reprocessed to increase the signal/noise ratio, thereby enhancing attribute characteristics.

Two hundred and ninety meters of high-quality core, a specialized log suite, fluid samples, and a diverse set of analytical laboratory measurements and petrographic observations were retrieved from the stratigraphic test well. As a result, velocity-porosity relations established from log data for different rock types have allowed us to use seismically-derived interval velocities for porosity estimates along targeted stratigraphic intervals (**Figure 3**). From these relations, 3-D spatial distribution volumes of reservoir and confining layer properties (property models) were constructed that yield an improved understanding of geological heterogeneity at the targeted CO_2 storage site (**Figure 3**).

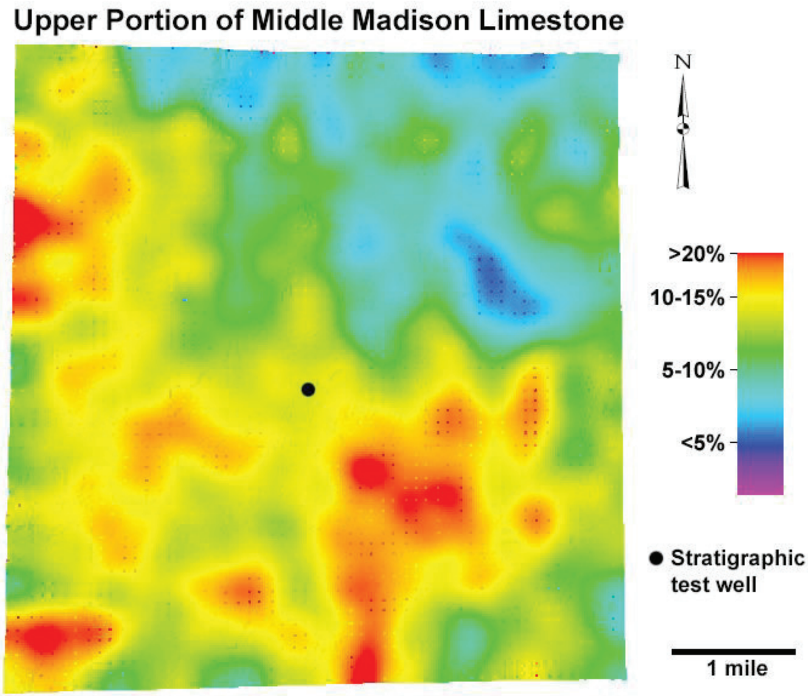

Figure 3. Surface from a porosity volume for the Madison Limestone (this slice represents porosity distribution of the upper portion of the Middle Madison Limestone). CMI scientists constructed the porosity volume by correlating 3-D seismic interval velocities with well log porosities to evaluate petrophysical heterogeneity . The black dot represents the location of the RSU#1 stratigraphic test well.

New CO_2 injection/storage performance assessments

The new CO_2 plume migration simulations – for a set of CO_2 injection rates and volumes – occupy larger rock/fluid volumes and display marginal irregularities when compared to early simulations derived from homogenous reservoir parameter volumes. For example, in the Madison Limestone, the spatial distributions of the injected CO_2 plumes in previous simulations are conical with few marginal irregularities, whereas in the new simulations, the CO_2 plumes occupy a substantially larger up-dip volume and display more marginal irregularities (**Figure 4**). These irregularities denote zones of higher porosity and permeability, such as collapsed breccias associated with karst zones and/or dolomitized zones in the Madison Limestone.

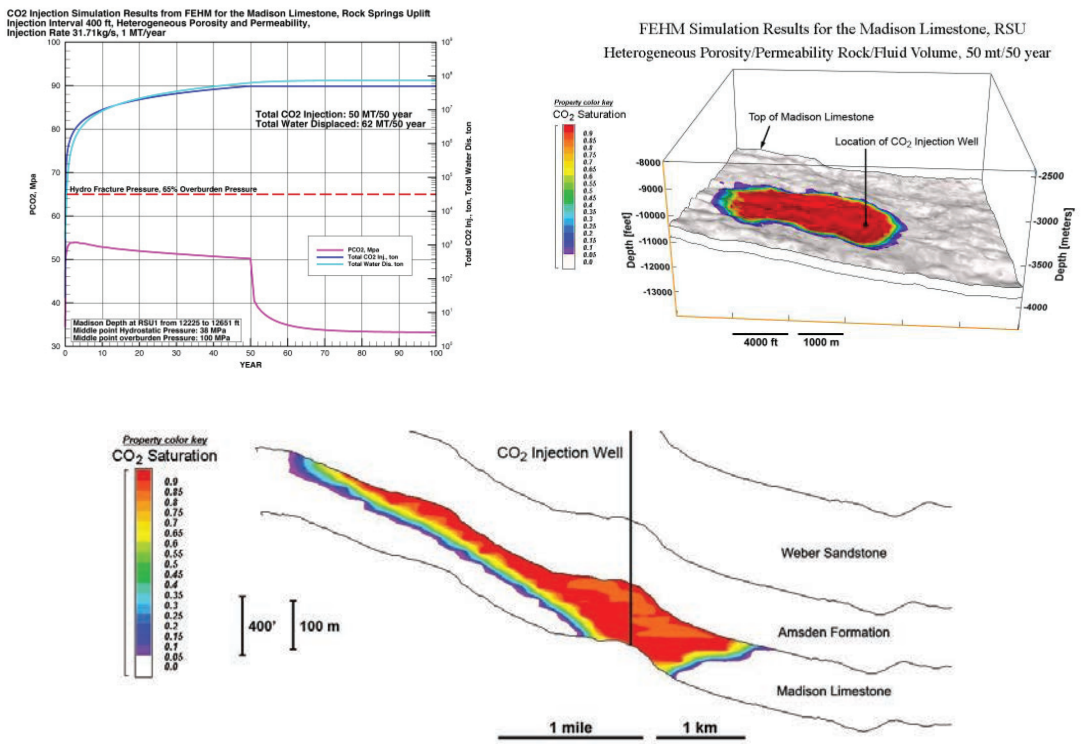

Figure 4. CO_2 injection simulation from LANL's Finite Element Heat and Mass Transfer (FEHM) software for the heterogeneous porosity and permeability volume of the Madison Limestone at the Rock Springs Uplift: a) change in pressure evolution, amount of CO_2 injected, and volume of displaced fluids over time, b) incline view of CO_2 plume on the top of the Madison Limestone, and c) up-dip cross section of the CO_2 plume.

Using the new numerical simulations including heterogeneous rock/fluid parameter distributions, all injection/storage scenarios of > 1 Mt/year CO_2 require substantial displaced fluid production/treatment to manage pressure and maintain the integrity of confining layers. The total dissolved solids concentrations of the formation fluids retrieved from the Madison Limestone range from 80,000 to 90,000 ppm, and will necessitate customized water treatment strategies and facilities at the surface. When compared with the initial CO_2 capacity evaluations, the new and much-improved performance assessments of both the Madison Limestone and Weber Sandstone reduce the estimated CO_2 storage capacity of the RSU by 50%. The new data and upgraded evaluations demonstrate that the Rock Springs Uplift in southwestern Wyoming remains an outstanding large-scale geological CO_2 storage site, and provides a realistic basis for designing commercial CO_2 injection/storage operations on the Uplift. Without pressure management, even at relatively low CO_2 volumes, the fluid injection causes the injection plume to approach fracture gradients quickly.

CCUS

The 2010 U.S. Environmental Protection Agency Greenhouse Gas Reporting Program reports that in the Greater Green River Basin of southwest Wyoming, the CO_2 emissions from stationary sources (sources that emit more than 25,000 tons of CO_2 per year) total 29+ million tons annually, or approximately 50 percent of Wyoming's annual CO_2 emissions. These CO_2 sources include coal-fired power plants, gas and trona processing plants, pipeline compression stations, chemical production facilities, and gas-field complexes, among others. The Rock Springs Uplift in the center of the Greater Green River Basin is ideally located to serve as a large-scale commercial geological CO_2 storage facility for half of all of Wyoming's industrial CO_2 emissions. The new numerical simulations suggest that the Madison Limestone has the ability to geologically store the annual CO_2 emissions from the Greater Green River Basin for 130 years (3.8 billion tons total). The overlying Paleozoic Weber Sandstone on the Rock Springs Uplift has additional commercial-scale CO_2 storage capacity.

Wyoming has 2 billion barrels of stranded oil ("pay zone" oil) that could be recovered via CO_2 flooding techniques, according to reports by the University of Wyoming Enhanced Oil Recovery Institute. If stranded oil in the "residual oil zone" is included, that amount could increase to 4–8 billion barrels of stranded oil in Wyoming. At present, Wyoming has 340 mmcf of CO_2 per day available from the ExxonMobil Shute Creek gas processing plant and 50 mmcf/day from the ConocoPhillips Lost Cabin gas processing plant. All of this CO_2 is under contract for existing EOR projects. Where will the CO_2 required to recover an additional 2–8 billion barrels of stranded oil in Wyoming come from? Denbury Resources plans to produce 600 mmcf/day at its Riley Ridge gas processing plant by 2017; however, the company intends to construct a 20-inch CO_2 pipeline to Montana to provide CO_2 to the Bell Creek, Cedar Creek Anticline, and beyond. Thus, at best, Wyoming may have 500 mmcf/day (26,300 tons/day) of CO_2 available for the next ten years, *most of which is already under contract*, and therefore unavailable for new EOR projects. However, assuming that this amount of CO_2 is available and that it takes 10 mcf of CO_2 to recover a barrel of oil, it will take 110 years to recover the 2 billion barrels of stranded oil in the pay zone, and 220 to 440 years to recover the stranded oil in the residual oil zone. In contrast, if the 1.2 bcf of anthropogenic CO_2 generated annually in southwestern Wyoming was captured and put to use, 2 billion barrels of stranded oil could be recovered in approximately 17 years.

A plan that requires serious consideration involves using the RSU as a CO_2 storage/surge tank: capturing the anthropogenic CO_2 currently emitted in southwestern Wyoming, storing it in the RSU, and retrieving it from storage on a schedule that optimizes the availability of CO_2 for tertiary recovery of stranded oil in Wyoming, particularly with respect to the Bighorn and Powder River basins. This plan has the following advantages: 1) it makes a waste product (CO_2 emissions) valuable; 2) it eliminates a critical shortage of CO_2 in Wyoming; 3) the CO_2 can be sequestered in the depleted oil fields once the stranded oil is recovered; 4) at least 2 billion barrels of stranded oil can be recovered in a timely fashion; 5) one half of the CO_2 emissions from stationary sources in Wyoming can be eliminated; and 6) the use of coal for power production in southwestern Wyoming can continue. When we objectively consider the "U" in CCUS, this plan deserves serious consideration.

Acknowledgments
The authors would like to thank the crew from Baker Hughes, Inc., including Paul Williams, Sam Zettle, Dana Dale, and Danny Dorsey. TRUE Drilling Co. of Casper, WY provided the large rig and an excellent drilling crew. The WY-CUSP characterization project is funded in part by the U.S. Department of Energy's National Energy Technology Laboratory (Project DE-FE0002142), and the authors would like to thank Project Manager Bill Aljoe. Other contributors include Los Alamos National Laboratory, Lawrence Livermore National Laboratory, PetroArc International, New England Research, Geokinetics, EMTek, and the Wyoming State Geological Survey. In addition, thanks to Dynamic Graphics for allowing us to use their EarthVision software and to Schlumberger for allowing us access to their Eclipse and Petrel software packages. Also, we acknowledge the support provided by the Wyoming Oil and Gas Conservation Commission and the Department of Environmental Quality. Lastly, but very importantly, we thank Shanna Dahl, Shauna Bury, Meg Ewald, and Allory Deiss – all colleagues at CMI – for their support, and Lynne Boomgaarden (Belcher & Boomgaarden LLP) for permitting assistance: without their contributions, this project would be impossible.

References
[1] Surdam, R.C. and Jiao, Z., 2007, The Rock Springs Uplift: An outstanding geological CO_2 sequestration site in southwest Wyoming: Wyoming State Geological Survey Challenges in Geologic Resource Development No. 2, 31 p.

[2] Surdam, R.C., Jiao, Z., Stauffer, P., and Miller, T., 2009, An integrated strategy for carbon management combining geological CO_2 sequestration, displaced fluid production, and water treatment: Wyoming State Geological Survey Challenges in Geologic Resource Development No. 8, 25 p.

[3] Stauffer, P.H., Surdam, R.C., Jiao, Z., Miller, T.A., Bentley, R.D., 2009, Combining geologic data and numerical modeling to improve estimates of the CO_2 sequestration potential of the Rock Springs Uplift, Wyoming: Energy Procedia 1(1) (2009), Elsevier, p. 2717–2724.

[4] Surdam, R.C., Jiao, Z., Stauffer, P., and Miller, T., 2011, The key to commercial-scale geological CO_2 sequestration: Displaced fluid management: Energy Procedia 4(1) (2011), Elsevier, p. 4246–4251.